

HEAT RESISTANT AIRFIELD PAVEMENT JOINT SEALANTS

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ABSTRACT

Fourteen types of commercially available elastomers were tested for chemical and thermal resistance. Initially, 13 polymers were placed in grooves on concrete samples and tested under heat on a small scale, and tested for degradation under exposure to jet fuel, engine oil, and hydraulic fluid. The top 8 polymers, together with 5 new ones, were then tested on concrete slabs under a simulated jet engine exhaust with a realistic heat flux. The purpose was to evaluate polymers that could be used to replace joint sealants damaged by Navy aircraft such as F/A-18, V-22, and AV-8B. The top materials included (a) fluorosilicones, (b) fluorocarbons, (c) a nitrile rubber, (d) vinyl and methyl silicones, (e) a chlorosulfonated polypropylene, and (f) chloroprene rubber, all of which were thermally stable at 550°F, or more. These materials were also resistant to jet fuel, hydraulic fluid, and engine oil, although the silicones showed jet fuel absorption. The fluorosilicones and fluorocarbons survived heating up to around 750°F. The nitrile and chloroprene rubbers survived temperatures up to 650 and 550°F, respectively. The vinyl and methyl silicones survived up to 600°F. The fluorosilicones and fluorocarbons are very expensive, but the chloroprene and nitrile rubbers are economical choices for new pavements, and the vinyl and methyl silicones cost little more than Federal Specification SS-S-200E materials with much improved performance. For F/A-18, B-1, and V-22 aircraft applications, the vinyl and methyl silicones are recommended for both new and existing pavements, whereas the chloroprene preformed seal is recommended for new pavements.

INTRODUCTION

Slabs in concrete airfields are limited in size (typically 12.5'x15' for Navy and Marine Corps airfields) and separated by joints to relieve stresses due to thermal variations and curling. The pavement joints are usually sealed with elastomeric (rubber polymer) materials to prevent the ingress of water or incompressible materials (dirt, gravel, and other debris), which can result in slab edge cracking. If not prevented, edge cracking can result in the formation of foreign object debris (FOD), such as gravel and concrete particles. If FOD is swept into the aircraft's engines, considerable damage could result, requiring expensive repairs and aircraft downtime. Among the joint sealants currently used are combinations of polysulfide rubber and coal tars, silicones and a pre-formed joint seal made of neoprene (chloroprene rubber). The standard joint sealant (Federal Specification SS-S-200E) is a generic product that is used for concrete airfields, highways, and bridge decks [1]. This specification describes the basic physical properties for a "cold applied, two-component joint sealant" that solidifies to form a solid rubber (elastomer).

Modern Navy and Air Force pavements and joint sealants are being damaged by high temperature aircraft engines from vertical take-off aircraft such as the V-22 Osprey and AV-8B Harrier, and from the auxiliary power unit of other aircraft such as the F/A-18 and B-1 bomber, which are directed down towards the pavement (Figure 1). The pavement joint sealants can also be damaged by aircraft fluids, such as fuels, engine oil, or hydraulic fluids. Temperatures on the pavement vary from around 300°F for the V-22, around 345°F for the B-1 and the F/A-18, and up to about 900°F for the AV-8B. The Joint Strike Fighter is expected to exceed those temperatures, but was not addressed here. Sealants able to withstand 400°F or more would be good solutions for the V-22, F/A-18, and B-1.

Thirteen commercially available elastomers (polymers, or rubbers) were tested for chemical and thermal resistance on concrete samples in the laboratory. The top eight polymers and five new ones were then tested on larger concrete slabs and blocks under a simulated jet engine exhaust (gas burner) with a realistic heat flux [2].

TEST AND EVALUATION PROGRAM

The test and evaluation program involved two phases, including (a) a laboratory screening method for commercial elastomeric polymers (elastomers) and (b) exposure to the heat and gas exhaust of a full scale simulated jet engine outdoors. The laboratory screening methods were performed on elastomers placed into a simulated joint on small concrete plates. The sealants were tested for heat resistance and chemical resistance. The top candidates were then tested in the larger apparatus outdoors. For environmental purposes, the gaseous decomposition products were characterized by mass spectroscopy-gas chromatography (MS-GC).

Laboratory Thermal Tests

Concrete panels, 6- by 6- by 1-inch thick, were saw-cut from cured, non-reinforced concrete beams. A slot, 0.25-inch wide and 0.25-inch deep, was cut down the center of each panel. Various commercial elastomers were then used to fill the joints. These included both liquid mixtures that cured to solid elastomeric rubbers (typically used for existing pavements), and solid, preformed elastomeric rubbers (typically used for new pavements).

A standard coal-tar/polysulfide rubber meeting Federal Specification (FS) SS-S-200E was used as a control. Two commercial silicones (a high modulus and a self-leveling type) were also used [3, 4, 5], as was a commercial preformed neoprene seal [6]. Other sealants used included (a) a liquid fluoropolymer, (b) a solid fluoropolymer, (c) a polyacrylonitrile (nitrile) rubber, (d) other chloroprene products, (e) a polyolefin (ethylene-propylene dimmer, or EPDM) and (f) other fluoropolymer rubbers.

The concrete panels were heated by a small, high-temperature heat gun in a closed loop, direct digital control system (Figure 2). The temperature maxima and times were pre-set and controlled by a thermocouple placed along the joint. The maximum temperature would be reached within 2 minutes of heating, and the maximum heating time was limited to 3 minutes. The samples were first heated to 400°F and then inspected for heat damage. Next, the samples were heated to 500, 600, and 700°F.

Laboratory Chemical Tests

The elastomers were cut (all cured samples) into 1- by 0.375-inch strips, weighed, and placed in Pyrex glass test tubes. The samples were individually covered under 5 milliliters or more of:

- JP-5 jet fuel (MIL-T-5624) (Figure 3)
- Aircraft engine oil (MIL-H-83282) (Figure 4)
- Red hydraulic fluid, (MIL-L-23669) (Figure 5)

After 24 hours of immersion at 77°F (25°C), the sample specimens were removed from the test tubes, patted dry with absorbent paper towels, and re-weighed. Elastomers that were not degraded at 77°F (25°C) were also tested (using new samples) in water, engine oil, and hydraulic fluid at 140°F (60°C). The elastomers were evaluated for changes in physical (dimensional changes) and chemical properties (solution, gelation and swelling).

Large Scale Tests

After the results were tabulated for the 13 elastomers and controls, the top 8 elastomers were selected for large-scale tests (Figure 6). An additional 5 new elastomers were selected (4 fluorosilicones and one chlorosulfonated polypropylene). Larger, circular concrete slabs, 24 inches in diameter and 6 inches thick, and later 12- by 12- by 6-inch blocks, were cast and cured. Two joints were cut in a cross pattern (0.5-inch wide and 1-inch deep) on the surfaces of the concrete specimens. Four different elastomers were then applied to the four slots (simulated joints). The liquid elastomers were poured into each slot, but a small concrete or “rubber stopper” was placed in the center, so that the materials would not mix while they were curing. The concrete slabs were then heated to a maximum of 3 minutes at each temperature level (400 to 700°F, or up to 800°F if the material did not decompose) and the materials were inspected after each series of heating tests.

These tests were conducted using a large size gas burner in NFESC’s High Temperature Jet Exhaust Simulation Facility (HTJESF) in place of the laboratory hot air gun used in the laboratory tests. The HTJESF is a large natural-gas burner that was designed to simulate the exhaust heat flux of a full-scale aircraft engine [7] (Figure 6). Previously, it had been used by the NFESC to simulate the effects of an F/A-18 APU and AV-8B exhaust for testing heat resistant concrete pavements [8, 9], and in environmental studies to model air pollution by jet engines.

Concrete panels were placed on a cart and moved under the burner for the three-minute heating cycles, and pulled back for the 20 minute cooling cycles. The concrete panels were about 18 inches from the burner nozzle. Thermal damage was determined by physical inspection of the sealants after each run. Types of damage observed included (a) melting, (b) bubbling, (c) softening, (d) hardening, (e) smoke formation, (f) burning, (g) and cracking of the polymers. In most cases, visible decomposition was observed while the polymer sealant was being heated. In other cases, the sealant was carefully examined after the panels had cooled down.

LABORATORY TEST RESULTS

A summary is given below for each elastomer.

1. Coal tar-polysulfide (SS-S-200E): The coal tar-polysulfide smoked and softened at 400°F and melted at 480°F (Figure 7). It also absorbed oil, fuel, and hydraulic fluid. The JP-5 fuel dissolved the coal tar. At higher temperatures this sealant started dissolving in hydraulic fluid and engine oil. According to FS SS-S-200E, this material should have resisted 500°F, but a previous assessment of a dozen joint sealant products claiming to meet FS SS-S-200 (version E or earlier) also found many of them not appropriate for high temperature pavement use [10].
2. Methylsilicone: This self-leveling silicone blistered and puffed at 400°F but did not decompose until around 600°F. It absorbed appreciable amounts of JP5 fuel and softened. This silicone also absorbed some hydraulic fluid but very little engine oil.
3. Butyl (Bromobutyl) Rubber: Butyl rubber changed from white to red-brown at 400°F and began to melt around 450°F. Butyl rubber absorbed fuel, hydraulic fluid (it turned to a gel), and oil at high temperature.
4. Nitrile rubber: The nitrile rubber had better than average heat resistance and solvent resistance properties. It was heat resistant up to 500°F, but showed signs of cracking at 600°F. This nitrile rubber was not affected by engine oil, fuel, or hydraulic fluid.
5. Neoprene 1: This first neoprene was unaffected by heat up to 500°F but showed signs of cracking at 600°F. The neoprene absorbed only small amounts of oil, fuel and hydraulic fluid.
6. Neoprene 2: The second neoprene rubber had properties similar to the first one. This neoprene was thermally stable up to 400°F but buckled and bubbled slightly at 500°F. Small cracks were seen at 600°F. This neoprene was not affected by immersion in oil, fuel, or hydraulic fluid.
7. EPDM (white rubber): This EPDM rubber deteriorated at moderate temperatures (Figure 8). The white EPDM rubber actually started melting around 400°F. The white EPDM rubber absorbed substantial amounts of jet fuel and hydraulic fluid after 24 hours of immersion, and turned to a gel in JP5 fuel after 24 hours of exposure.
8. EPDM (black rubber): The black EPDM resisted heat up to 500°F with no apparent changes. A white surface char appeared around 540°F. The black EPDM rubber absorbed small amounts of jet fuel and hydraulic fluid but absorbed little engine oil.
9. Vinylsilicone: This silicone showed signs of bubbling around 400°F. It puffed up a little and discolored around 500°F. However, this silicone was heated to 600°F without decomposition and returned to its original consistency when cooled to room temperature. The silicone absorbed jet fuel but little hydraulic fluid and very little engine oil.
10. Fluorocarbon rubber: The fluorocarbon rubber showed no changes when heated to 400, 500, and 600°F but there was slight buckling at 700°F. The fluorocarbon rubber did not absorb engine oil, fuel, or hydraulic fluid.
11. Fluorocarbon caulk: The fluorocarbon caulk is similar in formulation to the solid rubber, and has a similar appearance once it has cured. It was stiffer and less pliable than the silicones. The caulk was stable up to 600°F without any observable changes. The caulk lost some weight (less than 0.1 gram) after soaking 24 hours in oil, hydraulic fluid, and jet fuel. There were some minor white stains after immersion in oil. The caulk was stiffer and much more viscous than the silicones – it was difficult to mix and apply, and had to be tamped down with a spatula. When it cured to a solid, it was relatively inelastic.
12. Fluorocarbon adhesive: The fluorocarbon adhesive is a two-part liquid consisting of the monomer and a curing agent or catalyst. The adhesive did not show signs of decomposition after being heated to 500, 600, and 700°F.

The adhesive lost less than 0.1 gram of weight after soaking 24 hours in oil, jet fuel, or hydraulic fluid. Some minor white stains formed when immersed in oil, but these could be wiped off. The adhesive contains methyl ethyl ketone (MEK), which evaporates as the product cures to a rubber.

13. **Modified epoxy putty:** This putty was difficult to mix and apply. It must be heat cured at 400°F in order to attain high temperature heat resistance. It showed no signs of deterioration or decomposition at 500, 600, or 700°F but it did harden around 600°F. This modified epoxy putty was not affected by fuel but absorbed engine oil and hydraulic fluid. The cured putty was too stiff to be used as a joint sealant.

Subsequently, four additional high temperature fluorosilicones and a pre-formed chlorosulfonated polyethylene (CSP) were later procured and tested for chemical exposure. None of these new materials absorbed any significant amount of fuel, oil, or hydraulic fluid.

LARGE SCALE TEST RESULTS

Joint Sealants Selected for the Tests

A total of eight elastomers were chosen from the original thirteen laboratory tests. The other elastomers were eliminated because they did not survive three minutes of heating at 500°F. The modified epoxy putty was eliminated because it hardened and became brittle at higher temperatures. The remaining eight elastomers were divided into two groups, Group A consisted of liquid or partly liquid polymers that cure to solid rubbers, and Group B consisted of pre-formed solid synthetic rubbers. Additionally, four new high temperature fluorosilicones and a pre-formed chlorosulfonated polyethylene (CSP) were procured and tested. The CSP was procured on the advice of the manufacturer, as a substitute for the more expensive fluorosilicone rubber, which they also manufactured.

Group A (liquids, gels and caulks)

- Methylsilicones
- Vinylsilicones
- Fluorosilicones
- Fluorocarbon adhesive
- Fluorocarbon caulk

Group B (solid, pre-formed rubbers)

- Fluorocarbon rubber (polyfluoroethylene)
- Nitrile rubber (polyacrylonitrile)
- Chloroprene rubber (neoprene)
- EPDM rubber (ethylene-propylene dimer)
- Chlorosulfonated polyethylene (CSP)

Group A (Liquids, Gels and Caulks)

The silicones were grouped together. A number of companies sell silicone joint sealants, unfortunately, it was not possible to test all the commercially available silicones. In the following tests, representative silicones (two companies) were selected that met the guide specifications. Since the major silicones are limited to methyl, phenyl, and fluorosilicones (trifluoromethyl), it is assumed that other commercial silicones would behave similarly in the heating tests.

Silicones

Commercial silicones are all described as being thermally stable to 600°F, although they tend to puff and bubble as low as 400°F.

One methylsilicone appeared to “sweat” or exude a liquid at 400°F, while the other was unaffected. Although both silicones puffed up, they shrank back into the joints after they cooled to room temperature. At 500°F, the methylsilicones bubbled and puffed up even more, but typically shrank back to their original volume after they cooled back down. At 600°F, the methylsilicones puffed and liquefied, or appeared to melt. The first signs of decomposition (slight smoking) were noticed above 600°F.

The gray vinylsilicones appeared pockmarked and distorted after heating, but they did not appear to decompose at 400°F. At 500°F, they also bubbled and puffed up even more, but shrunk back to their original volume after cooling down. At 600°F, the vinylsilicones puffed, liquefied or appeared to melt. One vinylsilicone separated from the joint and lost adhesion upon cooling. The first signs of decomposition (slight smoking, charring, production of white silica powder) were noticed above 600°F. The vinylsilicones appeared slightly more thermally stable than the methylsilicones.

Four new fluorosilicones were also tested. One was stable at 800°F and one started to darken and curl around 750°F. The other two withstood heating at temperatures up to 650°F.

Other Fluorocarbon Products

Fluorocarbon elastomers are commercially available in solid, caulk, and adhesive form (manufactured by the same company). The adhesive is somewhat like a “rubber cement”. The liquid sets to a rubbery solid after the solvent has evaporated. The caulk is a thick, viscous, black material that resembles a paste or clay. It was difficult to apply to the joints, using a trowel. The liquid adhesive was easily poured into the joint. Although the manufacturer recommended heat curing at 400°F, this material was heat cured by the gas burner during the testing. There was some shrinkage of the adhesive at room temperature, probably due to solvent evaporation.

The cured fluorocarbon adhesive was thermally stable at 500, 600, and 700°F, although some cracks appeared (Figure 9). However, when the cured adhesive was heated to 800°F for 2 minutes, it decomposed by smoking and cracking. The maximum temperature before decomposition was found to be about 750°F.

The fluorocarbon caulk was thermally stable at 500°F and 600°F, but it appeared to powder and flake above 600°F. The surface of the concrete, near the joint, appeared to be sprayed with a black powder after heating at 600°F or above. It was thought that the caulk had become brittle. The top surface of the caulk appeared to have sheared off and blown over the concrete surface by the exhaust gas pressure.

Group B (solids)

The tests were conducted at 100°F increments, up to 800°F or whenever decomposition would occur. The following observations were made per elastomer type:

1. EPDM (ethylene-propylene dimer) rubber: The black EPDM rubber behaved much the same as it did in the laboratory tests. The EPDM survived at least 10 cycles at 400°F but started to smoke after 1 cycle at 500°F. A white crust formed on top of the black sealant at 600°F as it did during in the lab tests. The white material is probably inorganic filler, such as silica or alumina.
2. Neoprene: The commercially available 1-inch chloroprene compression seals were easily inserted in ½-inch wide joints. They were not dislodged at nozzle exit flow velocities of 560 ft/sec (nozzle for the F/A-18 simulation). The nozzle velocities were calculated using the data for a 2-inch orifice plate (Cooper, 1996). Two different neoprene samples were tested – both neoprene samples easily survived 20 thermal cycles (3 minutes of heating and 20 minutes of cooling) at 400°F. Some small surface cracks appeared at 500°F after 5 cycles. The neoprene samples started smoking after 1 cycle at 550°F, so the heating tests were halted.
3. Nitrile rubber: The nitrile rubber survived 20 cycles of heating at 400°F and 10 cycles of heating at 500°F. Some surface cracking was seen after 5 cycles at 600°F. At 650°F, the nitrile rubber began to smoke and flake away as it decomposed.
4. Fluorocarbon rubber: The fluorocarbon rubber survived 20 cycles of heating at 500°F without decomposition. No damage was seen after 10 cycles of heating at 600°F. Some surface changes were observed after 3 cycles of heating at about 700° F. The fluorocarbon rubber decomposed after only 2 minutes of heating at 800°F. The actual maximum temperature was found to be about 750°F. The fluorocarbon rubber was as heat resistant as the fluorocarbon adhesive. The adhesive is easier to use, because it is a liquid, but the expense of the fluorocarbons may still prohibit use except for limited pavement joint areas requiring very high heat resistance.
5. Chlorosulfonated polyethylene (CSP): This pre-formed rubber decomposed at temperatures near 600°F. Although it was more thermally stable than some of the other elastomers, it was not a replacement for the fluorocarbon and might not be cost effective when compared with the nitrile and chloroprene rubbers.

Overall, the newer fluorosilicones were the most thermally stable, followed by the fluorocarbons (rubber, adhesive and caulk), the nitrile rubber, the vinylsilicones and methylsilicones, CSP, and then the chloroprene (neoprene) and EPDM rubbers.

Approximate temperatures and ranking are: fluorosilicones (650-800°F) > fluorocarbon rubber and adhesive (750°F) > nitrile rubber (650°F), vinylsilicones and methylsilicones (600°F) > chlorosulfonated polypropylene (600°F) > chloroprene (550°F) > black EPDM (500°F).

THERMAL DECOMPOSITION PRODUCTS FROM THE ELASTOMERS

Since there are strict environmental controls for air pollution in many regions, it was important to identify the vapor phase decomposition products from the combustion of the elastomeric products at very high temperatures. These are temperatures at which the AV-8B could operate. Small samples of the various elastomers were sent to an outside air quality laboratory (contractor). The contractor heated the products at 1,000°F and determined the various gaseous by-products using gas chromatography-mass spectrometry (GC/MS). The elastomers were each thermally decomposed (at 1,000°F) in a ceramic tube. The gaseous decomposition products were fed into the GC/MS spectrometer. The GC/MS instrument was automatically programmed to generate the mass fragment data. The data was then sorted according to molecular weights of the mass fragments. All possible compounds were printed out. NFESC did further sorting to identify the most likely by-products for each elastomer.

Almost all of the elastomers produced air pollutants at very high (1000°F) decomposition temperatures. Some of the chemicals appeared to be traces of solvents driven off by heating at lower temperatures (500 to 600°F).

The coal tar-polysulfide (FS SS-S-200E) produced various thiols, alkyl and aryl mercaptans and disulfides (sulfur-containing) compounds. The butyl rubber produced several bromoarenes, bromoalkanes and bromoalkenes (brominated compounds). The chloroprene (neoprene) produced chloroalkanes and chloroalkenes and some hydrogen chloride. The fluorocarbons produced fluoroalkenes, fluoroacetates and some fluoroalkanes. Decomposition of the fluorocarbons and fluorosilicones occurred around 800 to 1000°F. Only the hydrocarbon rubbers (EPDM) and the silicones decomposed to water vapor and carbon dioxide (plus silica for the silicones). However, it is important to note that potential pollutants are generated only on decomposition of neoprene and fluorocarbons at very high temperatures. This would only be a problem on pavements using the AV-8B, assuming that the pavement temperature reaches around 900°F.

Pollutants are not produced at lower temperatures, such as on airfield pavements deploying the F/A-18, B-1, and V-22 aircraft (up to 350°F). At these lower pavement temperatures, thermal decomposition is not likely for the nitrile, chloroprene, silicone, and fluorocarbon products (adhesive, caulk or solid rubber).

COST FACTORS

A major concern is the cost of these joint sealant materials. Table 1 shows the relative costs of each material. The costs are compared on the basis of physical properties or specifications (e.g., liquid, gel or caulk, and solid rubber). These costs are for laboratory amounts of materials only and do not represent the cost of installation at the airfield. However, it has been reported that the cost of installing silicone joint seals on an airfield (all labor and materials) is about \$3.00/ft for 3/8-inch wide joints.

RANKINGS

The materials were ranked based on their overall physical and chemical properties in Table 2. For F/A-18, B-1, and V-22 applications, the fluorocarbons are probably too expensive, and some of the materials are not acceptable. Table 3 shows the recommended materials for these aircraft, ranked on cost as well as physical and chemical properties. Since the preformed neoprene and the two silicones are off-the-shelf products and perform close to the others, it is expected that they will be used more. For F/A-18, B-1, and V-22 aircraft applications, the vinylsilicone and methylsilicone are easy to place and are recommended for both new and existing pavements, whereas the chloroprene preformed seal is recommended for new pavements. These silicones and chloroprene were already recommended by the Tri-Services [3, 4, 5].

CONCLUSIONS

The large-scale test results closely paralleled the laboratory test results, with a few differences. The eight materials with the highest temperature resistance melted or decomposed at roughly the same temperatures. The black EPDM was thermally stable to about 500°F and showed some absorption. The chloroprene was stable to 550°F and showed little absorption. The CSP, methylsilicones and vinylsilicones are heat resistant up to about 600°F (with some blistering) and absorbed some fluids. The nitrile rubber was stable to about 650°F, with minimal fluid absorption. The fluorocarbon rubber was stable to between 750°F and showed very little absorption of fluids. The fluorosilicones were stable to between 650 and 800°F (for up to 3 minutes), depending on the brand.

Most of the elastomers tested in the large-scale specimens will survive brief pavement temperatures (3-minute exposures) of 400 to 600°F (silicones). The more expensive fluorosilicones are suitable for higher temperatures. However, there is also a higher cost for more heat resistant polymers. There is also a trade-off between elastomer flexibility and temperature: at higher temperatures, many of the elastomers hardened. At this point none of the elastomers will survive the heat of the AV-8B aircraft if the pavement temperature reaches 900°F or higher.

For F/A-18, B-1, and V-22 aircraft applications, the vinylsilicone and methylsilicone are easy to place and are recommended for both new and existing pavements, whereas the chloroprene preformed seal is recommended for new pavements. Other products exist that perform equally well (Table 3), but are not available off-the-shelf.

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Table 1. Material Costs

Material	Purchase Price	Comparison Cost per type	Comparison Cost per ft
<u>Liquids (Fed. Spec. SS-S-200E)</u>			
Fluorocarbon adhesive	\$50/pint	\$400.00/gal	\$5.03/ft ^a
Standard coal tar-polysulfide	\$19/gal	\$19.00/gal	\$0.48/ft ^a
<u>Gels & Caulks (UFGS 02982N)</u>			
Fluorocarbon caulk	\$190/20oz. tube	\$152.00/lb	\$5.06/ft ^b
Modified epoxy putty	\$25.00/11oz. tube	\$36.00/lb	\$1.20/ft ^b
Methylsilicone (self leveling)	\$24.50/20oz tube	\$19.60/lb	\$0.65/ft ^c
Vinylsilicone (high modulus)	\$22.00/20oz. tube	\$18.00/lb	\$0.60/ft ^c
Fluorosilicone	\$430/20 oz. tube	...	\$11.70/ft
<u>Solid Rubbers (ASTM D-2628)</u>			
Fluorocarbon rubber	----	\$56.00/ft ²	\$7.48/ft ^d
Nitrile rubber	----	\$8.37/ft ²	\$2.89/ft ^d
EPDM (black)	----	\$7.42/ft ²	\$2.72/ft ^d
Neoprene (A)	----	\$6.85/ft ²	\$2.61/ft ^d
Butyl rubber (bromobutyl)	----	\$6.50/ft ²	\$2.54/ft ^d
Neoprene (B)	----	\$4.89/ft ²	\$2.21/ft ^d
EPDM (white)	----	\$3.35/ft ²	\$1.81/ft ^d
Chlorosulfonated polyethylene	----	\$8.40/ft ²	\$2.90/ft ^d

^a Based on coverage per pint^b Based on coverage per 20 oz tube^c Based on coverage per gallon (from manufacturer)^d Based on same process for extruded neoprene seals (from manufacturers)
(see explanation below for actual cost of short run extruded polymers)**Disclaimer:** Some of the elastomers are available in bulk and prices will vary significantly from those shown.

Table 2. Ranking based on physical and chemical properties

Material	Rank	Cost (\$/ft)	Heat Resistance (°F)	Chemical Resistance
Fluorosilicone	1	11.70	650-800	High (est.)
Fluorocarbon adhesive	2	5.03	750	High
Fluorocarbon rubber	3	7.48	750	High
Fluorocarbon caulk	4	5.06	650	High
Nitrile rubber	5	2.89	650	Good
Chlorosulfonated polyethylene (CSP)	6	2.90	600	Good
Chloroprene (Neoprene)	7	2.41	550	Good
Vinylsilicone (high modulus)	8	0.60	600	Fair
Methylsilicone (self leveling)	9	0.65	600	Fair
EPDM black	10	2.72	500	Fair
Butyl Rubber (bromobutyl)	11	2.54	450	Poor
EPDM white	12	1.81	400	Poor
Coal tar-polysulfide (SS-S-200E)	13	0.48	400	Poor
Mod. Epoxy Putty (too stiff for sealant use)	14	1.20	600	Fair

Table 3. Recommended materials for F/A-18, B-1, and MV-22 based on cost and performance

Material	Approximate Cost (\$/ft)	Heat Resistance (°F)	Chemical Resistance	Commercial Availability
Vinylsilicone (high modulus)	0.60	600	Fair	Off the shelf
Methylsilicone (self leveling)	0.65	600	Fair	Off the shelf
Chloroprene (Neoprene) (B)	2.21	550	Good	Off the shelf
Chloroprene (Neoprene) (A)	2.61	550	Good	Must be extruded
Nitrile rubber	2.89	650	Good	Must be extruded
EPDM black	2.72	500	Fair	Must be extruded



Figure 1. Melted joint seals after exposure to high temperatures.

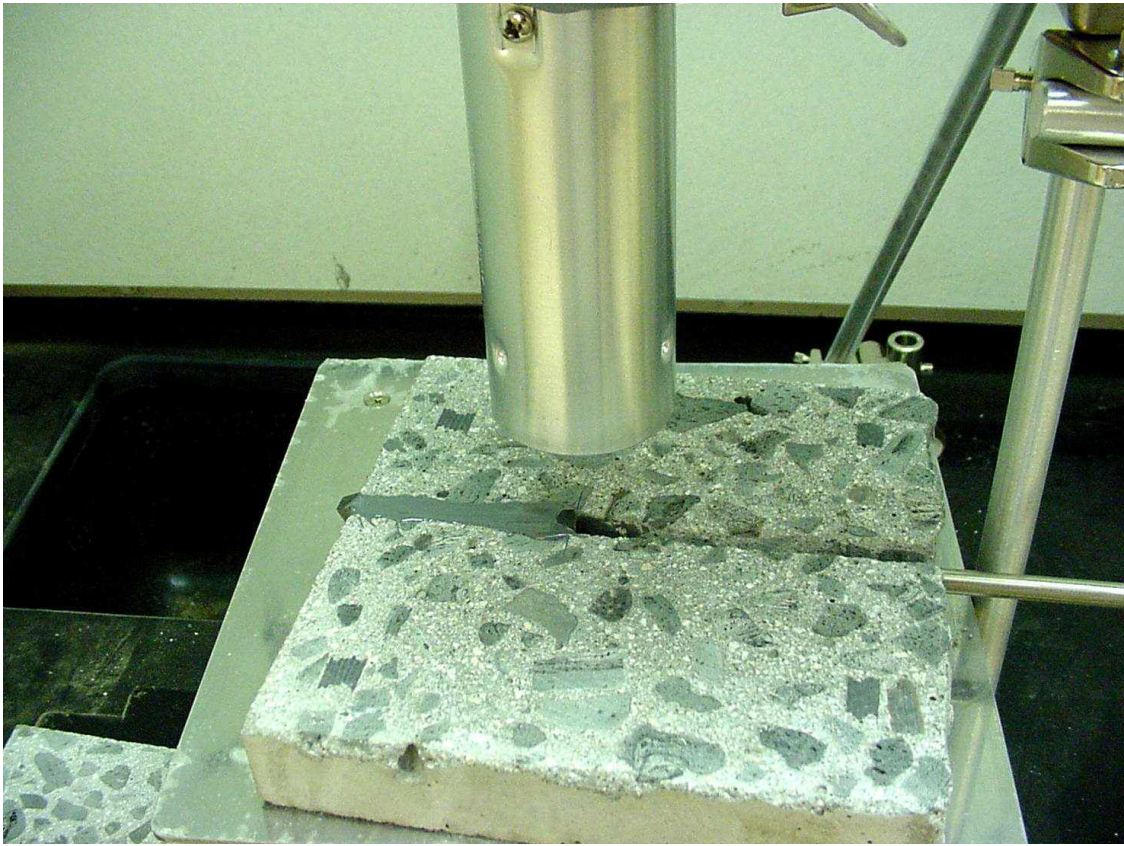


Figure 2. Laboratory thermal test setup.



Figure 3. Condition of elastomer test strips after soaking in JP-5 jet fuel.

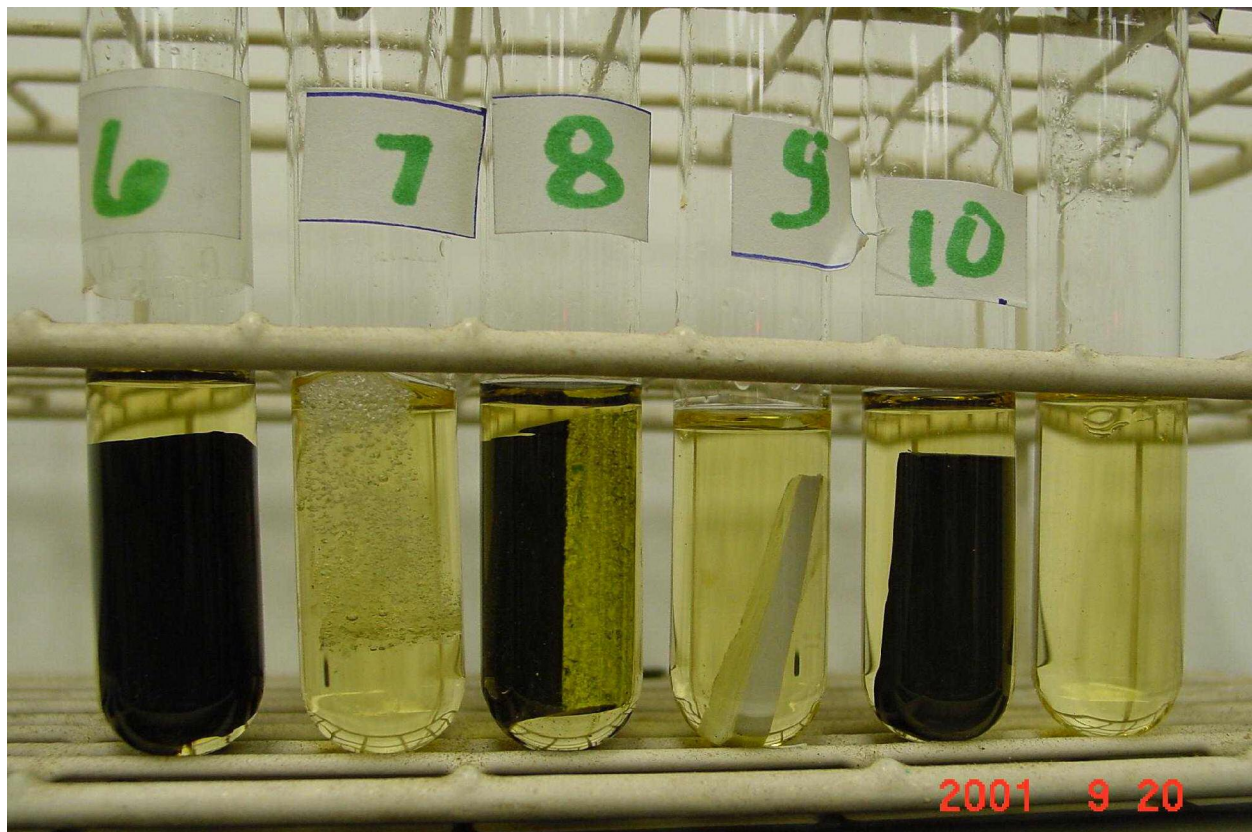


Figure 4. Condition of elastomer test strips after soaking in engine oil.



Figure 5. Condition of elastomer test strips after soaking in hydraulic fluid.



Figure 6. Large-scale test sample in HTJESF.



Figure 7. FS SS-S-200E sealant at 500°F.

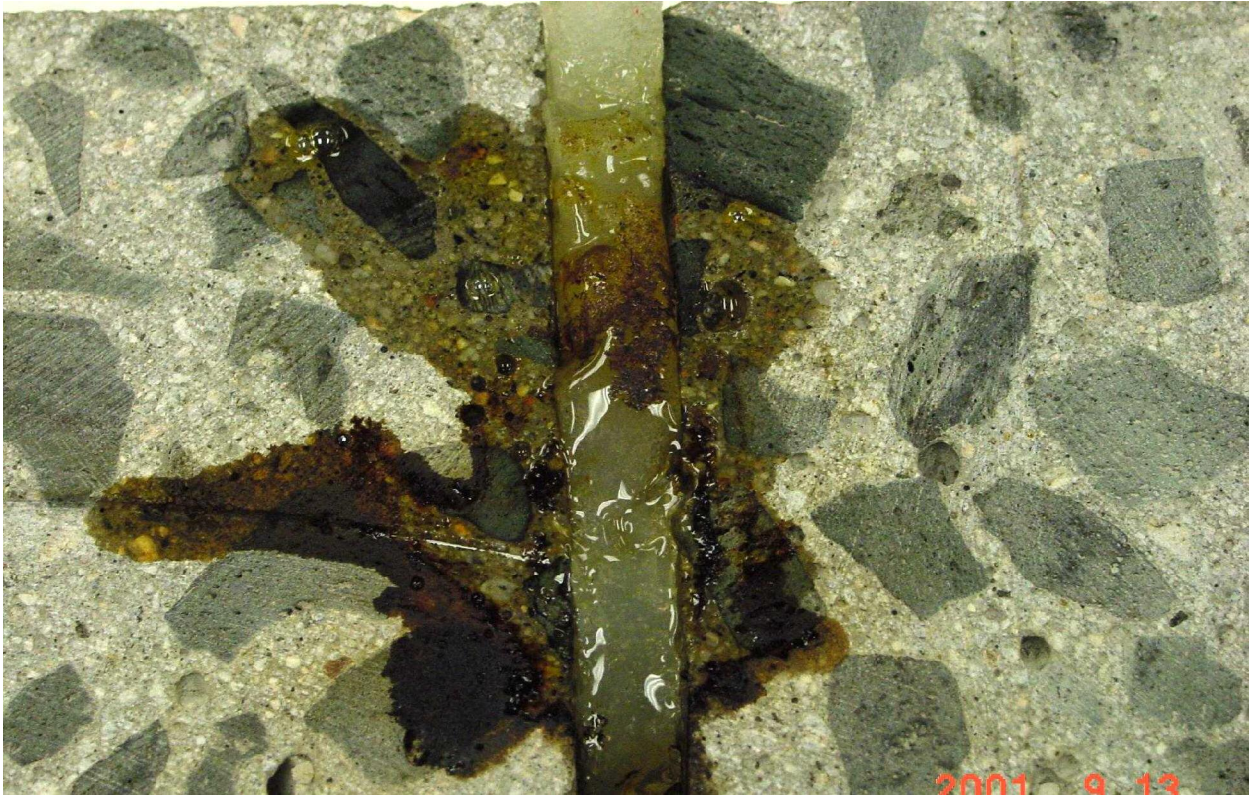


Figure 8. EPDM white at 500°F.



Figure 9. Fluorocarbon caulk and adhesive at 700°F.